DIVISION S-5—PEDOLOGY

Taxonomic and Geographic Distribution of Soil Organic Carbon Pools in Ohio

Zhengxi Tan,* Rattan Lal, Neil E. Smeck, Frank G. Calhoun, Brian K. Slater, Bob Parkinson, and Rich M. Gehring

ABSTRACT

Spatial distribution information about soil organic C (SOC) pools at a proper scale is critical for developing feasible C sequestration programs. This study characterizes the spatial variation in SOC pools related to soil taxon, Major Land Resource Area (MLRA), and land use. Grouping data by the land uses associated with soil orders within each MLRA leads to a statewide average SOC pool of 10.2 ± 2.8 kg m^{-2} in the upper 1-m depth, ranging from 7.1 kg m^{-2} in Ultisols to 117 in Histosols (8.8, 11.3, 12.7, and 16.9 kg m^{-2} in Alfisols, Inceptisols, Entisols, and Mollisols, respectively), and geographically varying from 7.7 kg m^{-2} in MLRA 124 to 12.0 in both MLRA 99 and 111. These variations can be also partially attributed to the properties for suborder differentiation. Moreover, land use effects are confounded by preferential selection of land for cropland use and site topographic features, resulting in a higher SOC pool in cropland (10.9 kg m^{-2}) than in both forestland (9.5 kg m^{-2}) and pastureland (8.4 kg m^{-2}). The grand total SOC storage in Ohio ranges from 853 to 881 Tg (1 Tg = 10^{12} g). The SOC pool is primarily related to landscape slope and soil drainage, and must be considered in interpretations for C sequestration potential among land uses for each soil taxon at the MLRA scale.

Regional assessments and spatial variability of SOC pools at various scales in the USA have been conducted using different approaches. Franzmeier et al. (1985) estimated the area-weighted SOC pool means of the upper 1-m depth of soils based on 199 mineral soil association map units and reported the geographic distribution of SOC pool sizes in the North Central USA in which Ohio soils were grouped into two SOC pool ranks: 5 to10 kg m^{-2} in the southeastern region and 10 to 15 kg m^{-2} in the northwestern region. Afterwards, Davidson and Lefebvre (1993) compared three methods (i.e., multiplying the area of the state by published means of soil C for temperate forests and Spodosols; calculating areas of inclusions of soil taxa in the 1:5 000 000 FAO/USESCO Soils Map of the world and multiplying those areas by selected mean C contents; and calculating soil C for each soil series and map unit in the 1:250 000 State Soil Geographic database [STATSGO] and summing these estimates for an entire state) to estimate SOC pools for the state of Maine. They found that the total SOC pool was at least 23% higher by the STATSGO approach than by other coarse scale approaches. Kern (1994) estimated SOC pools at a national scale using ecosystem complex and taxonomic approaches. Homann et al. (1998) compared six different approaches used in estimating SOC pools and spatial patterns in forested western Oregon and found that estimates by different approaches differed depending on the scale. They concluded that a rigorous testing of SOC maps requires data from pedons identified by objective criteria, in contrast to the subjectively located pedons. Brejda et al. (2001) suggested that the National Resources Inventory (NRI) would be an effective tool for estimating SOC pools under different land uses and conservation practices at a regional scale.

Currently, the soil taxa and their aggregation are increasingly applied to SOC pool estimation based on the hypothesis that the distribution of SOC pools spatially varies with soil taxa. However, the results derived from this data aggregation have not been adequate for the development of feasible land use plans for SOC sequestration. Areas defined by soil taxon map units often include all land uses and some SOC stocks in nonagricultural lands are included in the interpretation of SOC sequestration potential. In addition, well-known land use management effects on SOC sequestration and depletion within individual soil taxa are not considered. Furthermore, map units contain inclusions of different taxa.

Soil and agricultural resource condition on private lands in the USA are monitored by the USDA-NRCS using the NRI (Kellogg et al., 1994). More than 800 000 points have been established for the NRI and visited at 5-yr intervals to collect data. Though no soil samples are collected in the NRI, data on land use and conservation practices within each MLRA are collected at each site and summarized for each state. The NRI makes it possible to estimate the extent of various land use practices in taxonomic units and/or MLRAs for SOC credit accounting and SOC sequestration potential estimation.

The magnitude of SOC pool is a product of complex interactions among climate, topography, texture, and land-use practices (Parton et al., 1987; Burke et al., 1989; Pennock and van Kessel, 1997; Tan et al., 2003). Because of the strong influence of climate on SOC dynamics, a greater precision may be achieved if monitoring is conducted within the region containing similar climatic conditions (Brejda et al., 2001). The MLRA is a geographic unit that contains similar patterns of climate, soils, water resources, and land uses (USDA-SCS, 1981). It offers an appropriate regional scale unit for estimating SOC pools (Brejda et al., 2001).

A previous study showed that SOC pools vary signifi-

Z. Tan, R. Lal, N.E. Smeck, F.G. Calhoun, and B.K. Slater, School of Natural Resources, The Ohio State Univ., 2021 Coffey Road, Columbus, OH 43210; B. Parkinson and R.M. Gehring, USDA-NRCS, 200 N High Street, Columbus, OH 43215. Received 2 Apr. 2003. *Corresponding author (Tan.129@osu.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: MLRA, Major Land Resource Area; NRI, National Resource Inventory; SOC, soil organic carbon.

cantly with soil taxon and land use, and are significantly affected by drainage conditions in Ohio (Tan et al., 2003). To develop public policy for conservation programs, information is needed on spatial distributions and baselines of the SOC pools in association with soil taxon, land use, and MLRA at an appropriate level of data aggregation. The objectives of this study were to: (i) estimate SOC pool sizes by integrating the Ohio Soil Characterization Database with NRI and STATSGO map units, and (ii) identify regional distribution patterns of SOC pools in association with both land uses and soil taxa within individual MLRAs.

MATERIALS AND METHODS

Study Area

Ohio is located between 38°24′00″ to 41°58′48″N Lat. and 80°30′04″ to 84°49′16″W Long. and covers an area of 107 100 km^2, which has been regionalized into eight MLRAs according to common features in climate, topography, origin of soil parent materials, vegetation, etc. (Fig. 1). Regional physiography, geological characteristics, and soil parent materials have been described by Calhoun et al. (2001). Soils in Ohio have either a udic or an aquic moisture regime and a mesic temperature regime (Calhoun et al., 2001). According to the 1997 NRI–Ohio (USDA-NRCS, 2000), about 78% of all Ohio land area in 1997 was used for crop cultivation, pasture, and forests, which can contribute to SOC sequestration. The long-term records show that statewide mean annual precipitation is 979 mm, spatially ranging from 846 mm in the northwest to 1098 mm in the southeast, and mean annual temperature is 10.1°C, geographically fluctuating from 9.2°C in the north to 11.6°C in the south.

Data Source and Selection

Soil properties and site data were extracted from the Ohio Soil Survey Characterization Database (Calhoun et al., 1999). A total of 1432 taxonomically recognized pedons, including shallow soils with a lithic or paralithic contact deeper than 30 cm, were selected for this study. They were sampled between 1950 and 1990 and had original SOC measurements with all horizons within the upper 100-cm depth. Eighty-seven

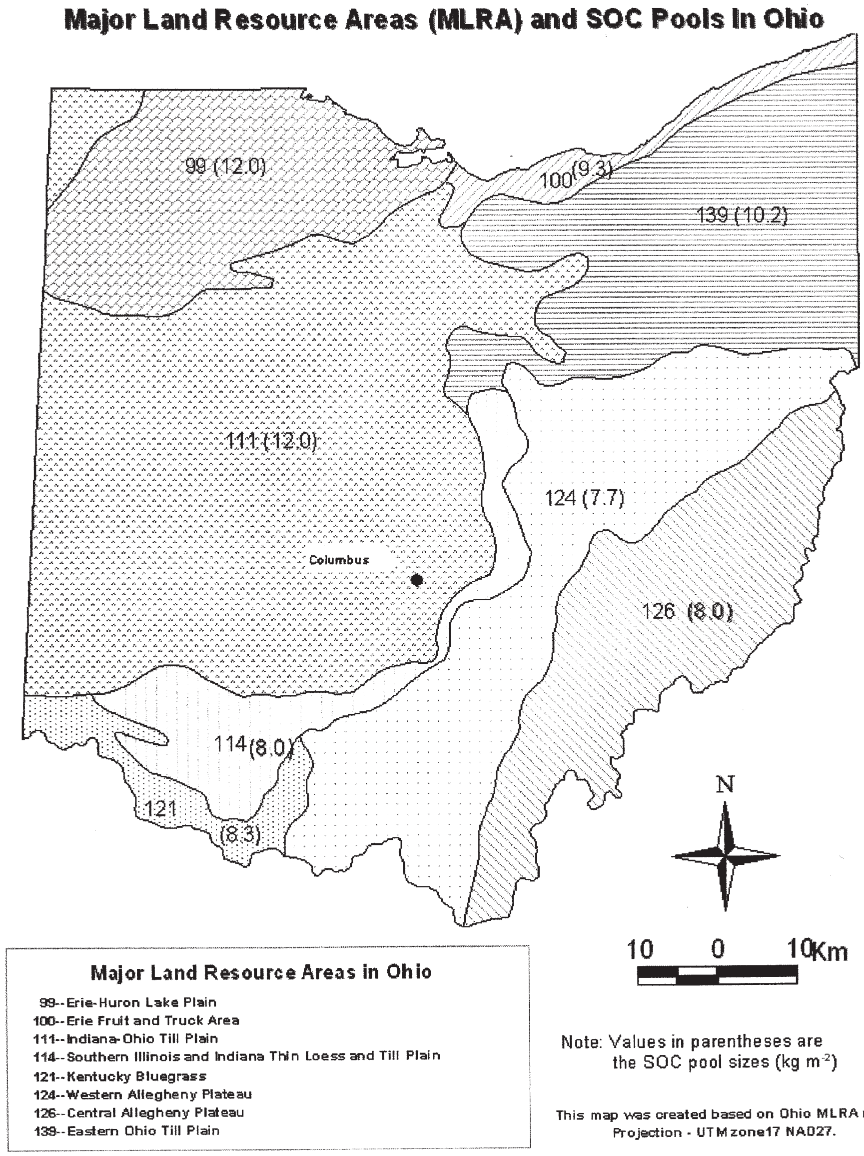

Fig. 1. Major Land Resource Areas (MLRAs) and magnitudes of soil organic C (SOC) pools estimated using the MLRA-taxonomic approach.

percent of these pedons were collected before 1980. All pedons are classified as Alfisols, Entisols, Inceptisols, Mollisols, Ultisols, or Histosols, and account for 69.2, 5.5, 8.3, 9.9, 6.8, and 0.3% of the state land area, respectively.

Soil Organic Carbon Pool Calculation

The SOC pool of the upper 100-cm depth for each pedon was calculated using following equation and expressed as a depth weighted mass on a unit area base (kg m^{-2}):

$$SOCP = \sum_{i=1}^{n} L_i \times SOC \times \rho_b \times (1 - F/100)/10 \quad [1]$$

where SOCP equals SOC pool to the 100-cm depth (kg m^{-2}); SOC equals SOC concentration (weight percent %); i is the i^{th} layer; n equals the number of layers involved in calculation; L_i equals the thickness of the i^{th} layer in centimeters; ρ_b equals soil bulk density, usually at 33 kPa suction (Mg m^{-3}); F equals >2-mm coarse fragment percentage (%); and $\Sigma L_i = 100$ cm, unless otherwise specified.

For horizons lacking bulk density data, the field model developed by Calhoun et al. (2001) using the same database as used in this study was used to estimate soil bulk density for horizons with SOC concentrations ≤60 g kg^{-1}. This model tends to underestimate bulk density as SOC concentrations increase. Therefore, the equation proposed by Adams (1973) was applied for horizons with SOC concentration >60 g kg^{-1}.

For shallow and steep soils with a lithic or paralithic contact whose depths are deeper than 30 cm, the SOC pools were computed using their actual sampled depths and included in the calculation of mean SOC pools.

Computation of Means of Area-weighted Soil Organic Carbon Pools

Data Aggregation Approach

The SOC pool means at the order or MLRA level were calculated with an area-weight because basic units for data aggregation may have different areas associated with individual taxa and MLRAs. For example, Histosols have very high SOC pool value (kg C m^{-2}) but their distribution areas for each land use category within each MLRA is very small, and

Table 1. Estimates of soil organic C (SOC) pools and total storage using the taxonomic approach.

Soil order	Suborder	Land use	N†	Area	Mean‡ Land use	Mean‡ Suborder	Mean‡ Order	CV§	Sum
				1000 ha	kg C m^{-2}			%	Tg C
Alfisols	Aqualf	crop	107	1547.1	9.6 j	9.8 e	8.8 e	14	510.2
		forest	43	462.8	10.8 i				
		pasture	167	131.0	9.6 j				
	Udalf	crop	168	1794.7	7.8 k	8.3 f			
		forest	143	1422.3	9.1 j				
		pasture	318	409.0	7.6 k				
Entisols	Aquent	crop	6	105.8	18.8 de	20.6 b	15.1 c	41	71.0
		forest	3	89.9	23.9 c				
		pasture	11	23.1	16.2 f				
	Fluvent	crop	1	44.7	19.4 d	17.4 c			
		forest¶		15.0	13.3 gh				
		pasture	3	5.7	12.3 h				
	Orthent	crop	3	26.2	12.0 hi	8.8 ef			
		forest	3	81.4	8.2 jk				
		pasture	11	22.8	7.6 k				
	Psamment	crop	2	40.5	5.5 lm	5.4 h			
		forest	3	13.1	4.9 m				
		pasture	7	2.5	6.3 l				
Histosols	Saprist	crop	4	17.0	116.8 a	113.4 a	113.4 a	23	27.4
		forest	1	5.7	115.1 a				
		pasture	1	1.5	69.8 b				
Inceptisols	Aquept	crop	51	212.2	15.2 fg	15.4 cd	12.4 d	23	86.2
		forest	8	35.5	16.8 ef				
		pasture	39	6.2	13.7 gh				
	Udept	crop	12	117.2	14.2 g	10.7 e			
		forest	35	258.0	8.4 jk				
		pasture	18	65.5	13.5 gh				
Mollisols	Aquoll	crop¶		612.3	17.2 ef	17.1 c	17.1 b	11	141.6
		forest	3	101.1	17.1 ef				
		pasture	2	41.5	16.2 f				
	Rendoll	crop	66	4.2	17.7 e	17.2 c			
		forest	8	0.4	13.5 gh				
		pasture	52	0.1	12.5 h				
	Udoll	crop	23	51.6	16.1 f	16.5 c			
		forest†		13.8	17.8 e				
		pasture	27	5.0	16.5 ef				
Ultisols	Aquult	crop	1	0.1	6.8 kl	7.1 g	7.1 e	9	42.5
		forest	1	0.2	6.9 kl				
		pasture	3	0.1	8.2 jk				
	Udult	crop	12	131.7	7.0 kl	7.1 g			
		forest	39	366.3	7.4 k				
		pasture	27	97.9	6.2 l				
	Overall		1432	8383			10.5	31	878.9

† Sample size.
‡ Area-weighted means, least significant difference (LSD) tested at $\alpha = 0.05$, and the same letters in the same column mean no significant difference between them.
§ Coefficient of variation (%) that is for SOC pool mean at order level.
¶ Estimated at order level because of no samples available.

to arithmetically average them with other orders will overestimate mean values at any higher data aggregation levels.

Calculations of area-weighted means and sums of SOC pool sizes were conducted and compared between land use categories using two data aggregation approaches:

1. Taxonomic approach, that is, to group pedons by suborders, then to classify those suborders into cropland, pastureland, and forestland.
2. MLRA-taxonomic approach, that is, to group pedons by soil order within respective MLRAs; then to classify those pedons that were defined by both MLRA and order into cropland, pastureland, and forestland.

Generation of Taxon–Land Use–MLRA Theme and Area Data

The taxon-land use theme and the taxon–land use–MLRA theme were created as follows:

1. Classify all pedons into respective suborders and orders.
2. Geographically locate each pedon on a 1:100 000 scale 30 by 60 min Quadrangle Topographic map according to initial records of sampling location, and relevant online USGS Quad maps were used to assist georeferencing. Meanwhile, the pedon location theme was integrated into STATSGO soil map to define the distribution (areal) boundary of each pedon, that is, the pedon theme.
3. Assign land use category to each pedon by intersecting the pedon theme with the National Land Cover Data 1992 (NLCD 92) theme that was previously converted from Geo-TIFF format (USGS, 2001), which resulted in the taxon-land use theme and its attribute table.
4. Assign a MLRA code to each pedon by intersecting the taxon-land use theme (generated from Step 3) with the MLRA coverage. Thus, the taxon-land use-MLRA theme was generated and each pedon record in the attribute table includes STATSGO map unit ID, taxonomic name and areal percentage of individual taxon components within a map unit, land use category, and MLRA code (also contains other attributes such as drainage class, site slope measurement, etc.). And all records were sorted and aggregated at suborder and order level for further use.

Computation of Areas of Land Uses Associated with Taxon and MLRA

The areas of individual suborders were directly derived from the attribute table of the pedon theme. Meanwhile, the baseline areas covered by individual land use categories at both the state scale and MLRA scale were adopted from the 1997 NRI–Ohio (USDA-NRCS, 2000). These area values were used to compute the actual areas of both the suborder-associated land uses within a particular order and the order-associated land uses within each MLRA.

Each suborder component under an order may be occupied not only by crop, pasture, or forest, but also by other land use categories, while the same land use may be distributed on different suborders. Therefore, the area of a suborder-associated land use under an order was calculated with such an assumption that every suborder contains the same relative proportion of a land use, as this land use constitutes the total area of Ohio. For example, the suborder SB, one of suborders of the order O, has been identified as cropland; it has been known that the area of the order O is Ao, areal percentage of suborder SB is Asb% of the area of the order O, the total land area of Ohio is A, and the area of cropland in Ohio is CP; assuming that the suborder SB under the order O contains same proportion of cropland as cropland proportion of total area of Ohio; then the actual area of the suborder SB-associated cropland should be $[(Asb\% \times Ao) \times (CP/A)]$. The estimated areas of the suborder-land uses are presented in Table 1.

Similarly, if the order O has been identified as cropland within MLRA 99, for example; it has been known that, within MLRA 99, the area of the order O is Aom, the total area of MLRA 99 is Am, and the area of cropland is CPm; assuming that the order O in MLRA 99 has same percentage of cropland as the percentage of all cropland in the MLRA; then the actual area of the order O-associated cropland within the MLRA should be $[Aom \times (CPm/Am)]$.

Table 2. Estimates of soil organic C (SOC) pools and total storage using the Major Land Resource Area (MLRA)-taxonomic approach.

Soil order	Land use	MLRA 99	100	111	114	121	124	126	139	Mean†		CV‡
		kg C m⁻²										%
Alfisols	crop	10.2	8.3	9.0	6.8	6.9	6.0	8.1	8.2	8.7	8.8	28
	forest	12.6	10.7	10.7	9.9	8.4	8.5	8.3	10.0	9.3		
	pasture	10.1	11.2	9.2	6.8	7.5	6.4	7.4	8.8	7.8		
Entisols	crop	7.6	8.6	20.1	9.2	7.8	14.5	10.8	20.0	14.7	11.6	32
	forest	11.4	8.6	19.6	11.5	8.6	2.5	8.2	20.3	9.0		
	pasture	9.7	8.6	19.3	12.7	8.7	5.3	8.3	8.3	8.9		
Histosols	crop	69.8		120					114	118	117	3
	forest			119					115	117		
	pasture	69.8		120					114	117		
Inceptisols	crop	14.5	10.2	19.1	9.8	9.4	15.9	4.6	13.1	14.3	11.3	28
	forest	18.4	6.5	20.4	5.4	9.8	7.6	9.0	11.1	8.8		
	pasture	14.6	12.7	19.3	12.1	12.3	4.9	11.6	10.1	7.7		
Mollisols	crop	17.7	10.5	16.7	20.8	18.9	15.8	10.8	22.4	16.9	16.9	26
	forest	13.5	15.3	17.7	18.9	18.8	15.4	13.5	20.8	17.4		
	pasture	12.5	20.1	16.8	13.3	20.0	15.0	14.4	16.1	16.7		
Ultisols	crop		7.0	14.9	7.9		6.7	7.7	5.8	7.3	7.1	28
	forest		4.5	16.5	7.3		7.5	6.8	6.3	7.3		
	pasture		8.3	13.3	8.2		5.9	6.6	2.9	6.3		
Mean†	kg C m^{-2}	12.0	9.3	12.0	8.0	8.3	7.7	8.0	10.6		10.2	
CV§	%	34	23	25	35	27	26	29	32			28
Area	1000 ha	937	95	3002	499	207	1428	1153	1062	8383		
C storage	Tg	112	9	361	40	17	109	92	113	853		

† Weighted by the area of each land use in association with orders and MLRAs, and LSD 0.05 = 1.1 for significance test between means.
‡ Coefficient of variation (%) that is for SOC pool mean at order level.
§ Coefficient of variation (%) that is for SOC pool mean at MLRA level.

Table 3. Soil organic C (SOC) pool sizes and their respective ground slopes for land uses associated with each soil order.

Order		Alfisols	Entisols	Histosols	Inceptisols	Mollisols	Ultisols
SOCP, kg m^{-2}†	crop	8.7	14.7	118	14.3	16.9	7.3
	forest	9.3	9.0	117	8.8	17.4	7.3
	pasture	7.8	18.7	117	7.7	16.7	6.3
Slope, %†	crop	2.2	3.9	0.0	1.1	0.7	2.8
	forest	11.6	14.9	0.0	31.0	0.6	18.4
	pasture	5.2	11.7	0.0	11.2	1.2	6.3

† Weighted by the area of each land use associated with soil orders within individual MLRAs. The slope data were obtained from individual pedons in the attribute table, and area for each land use associated with either suborder are the same as those for the computation of area-weighted averages of SOC pools.

The area data derived from above procedures were used to calculate the area-weighted means for SOC pool, drainage class, and slope, respectively.

Computation of Means of Area-weighted Soil Organic Carbon Pools

The mean of area-weighted SOC pool at different data aggregation levels was computed as follows:

$$SOCP_1 = \sum_{i=1}^{n} [(SOCP_i \times A_i)/A] \qquad [2]$$

where $SOCP_1$, the mean of area-weighted SOC pool for a suborder; $SOCP_i$, the SOC pool size under the i^{th} land use category; A_i, the area of the i^{th} land use category; A, the total area of all land uses associated with a suborder; n, the number of land use categories ($n \leq 3$).

Similarly, Eq. [2] was used to calculate the mean of area-weighted SOC pool for each order and MLRA.

Soil organic C content and the proportion among these three land use categories have, to a varying extent, been changed since the sampling date of each soil sample. These changes may have enhanced SOC sequestration in the targeted lands. However, the SOC depletion could also simultaneously occurred in other cropland and pastureland due to conventional tillage, overgrazing, etc., especially in the sampling period before 1980s. Therefore, all calculations of average SOC pools were computed by ignoring changes in land use and SOC dynamics.

The results of SOC pools for taxon-land uses and taxon-land use-MLRAs are presented in Table 1 and 2, respectively.

The procedures for area-weighted SOC pool calculation were also used to calculate the area-weighted drainage class and slope gradient at order level and MLRA scale. The results are presented in Table 3 and 4, respectively.

Finally, the geographic distributions of SOC pools associated with taxa (Fig. 2) and MLRAs (Fig. 1) were manipulated and visualized using ArcView 3.1 (ESRI, 1999).

Statistical Analysis

SAS software (SAS Institute, 2001) was used for statistical analyses. Analysis of variance (ANOVA) was performed on SOC pools for all pedons, of which general linear model (GLM) was used to calculate the means of SOC pools with suborder, order, or MLRA category as main effects, and mixed ANOVA models were used to compute and compare the means of SOC pools of suborders (and orders) associated with MLRA and land use category. Regression models were applied to analyze effects of either drainage condition or slope gradient on SOC pools. Fisher's least significant difference (LSD) was used to test whether means were considered significantly different at $\alpha = 0.05$.

Table 4. Ground slopes (%) for land uses associated with each MLRA.

MLRA	99	100	111	114	121	124	126	139	Mean†
Crop	0.9	0.9	1.7	1.7	1.9	4.1	5.5	2.9	2.0
Forest	0.3	14.1	2.2	11.5	11.8	21.1	20.6	4.4	14.2
Pasture	1.1	2.0	2.1	2.3	3.9	9.1	8.9	2.8	6.0
Mean†	0.8	7.5	1.8	4.7	7.0	15.8	15.6	3.5	6.5

† Weighed by the area of land uses distributed within each MLRA. The data source is the same as that for Table 3.

RESULTS AND DISCUSSION

Soil Organic Carbon Pool Distribution with Profile Depth

The taxonomic distribution pattern of the SOC pools stored in the upper 100-cm depth of soils is similar to that in the upper 30-cm depth reported by Tan et al. (2003). The SOC pool shows a consistent increase with soil depth, but the incremental increase with depth varies among soil orders (Fig. 3). The minimum cumulative rate is observed in Ultisols and the maximum in Mollisols excluding Histosols. Based on the SOC pools (arithmetic means) of the upper 1-m depth, the percentage of that in the upper 30 cm is 47, 57, 59, 63, and 67 for Entisols, Mollisols, Inceptisols, Alfisols, and Ultisols, respectively. Generally, about 60% of SOC pool in mineral soils is stored in the upper 30-cm depth of soils.

Taxonomic Distribution

The SOC pool sizes calculated for suborders and land uses using the taxonomic approach are summarized in Table 1. The means of SOC pools are presented at three data aggregation levels: land use within suborder, suborder, and order. Comparing SOC pool means within each suborder, significant differences among three land uses are only observed for Aquent, no significant differences for Aquult, and there are significant differences between two of three land use categories for other suborders. Soil organic C pool means at suborder level, regardless of land uses, significantly differ from each other within Alfisols, Entisols, and Inceptisols, and the largest variation is associated with Psamment. However, there are significant differences in SOC pool means among orders except for that between Alfisols and Ultisols. Excluding Histosols whose mean is 113 kg m^{-2} (Table 1), Mollisols have the highest SOC pool (17.1 kg m^{-2}) with the least variation among suborders though there is a large variation among land uses for suborder Rendoll, followed by Entisols in which, however, the highest CV (41%) is observed among suborders, while the lowest SOC pool mean occurs in Ultisols.

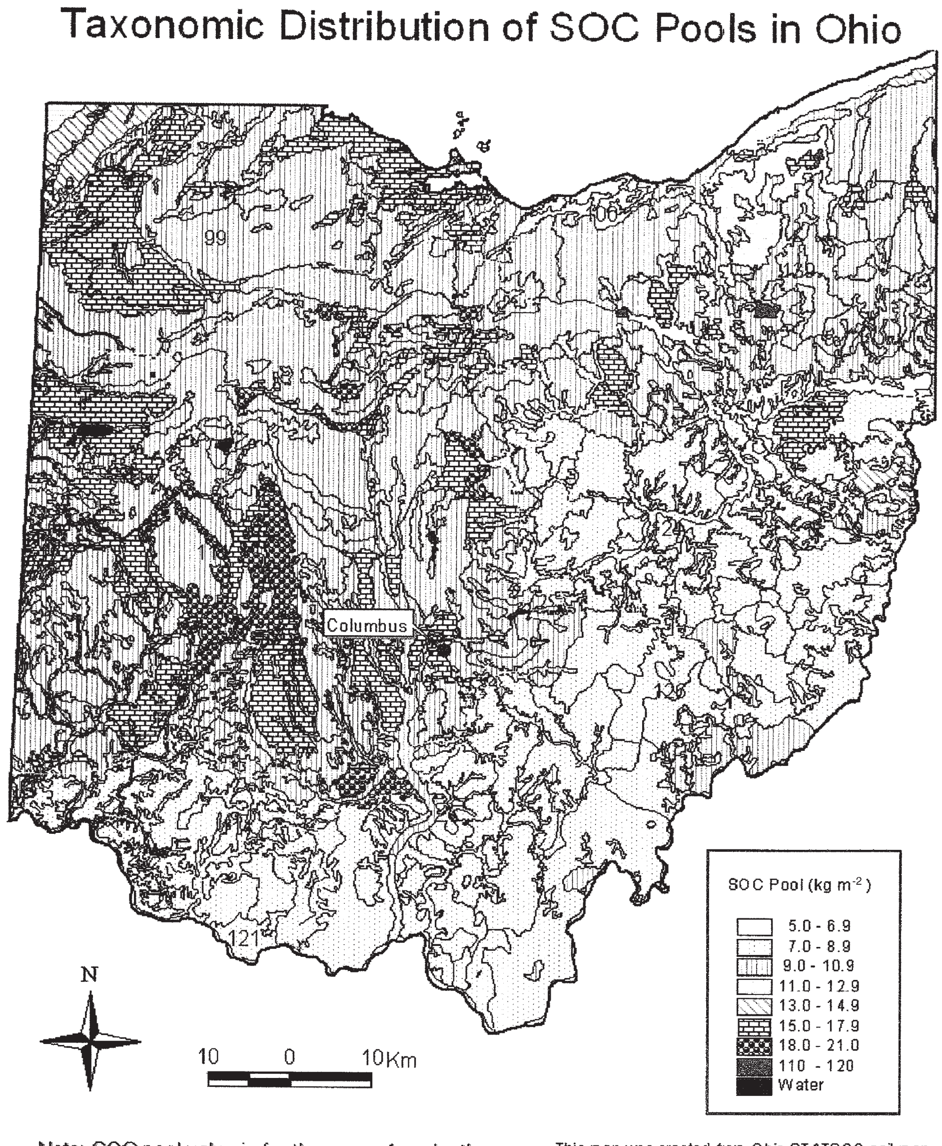

Fig. 2. Taxonomic distribution of soil organic C (SOC) pools estimated using the taxonomic approach and weighted by the area of each land use category within suborders.

Mollisols in Ohio are dominated by Aquolls and generally occur in level or gently sloping positions with poorly or very poorly drainage classes. Poor drainage favors SOC sequestration (Tan et al., 2003). Entisols and Inceptisols contain a high SOC pool because a large proportion of both orders in Ohio occur in floodplains where these soils are composed of surface sediments eroded from surrounding uplands. Similarly, SOC pool sizes can also be differentiated by other properties used to classify suborders for Entisols (Table 1).

Statewide, the mean of the SOC pool is about 10.5 ± 3.2 kg C m^{-2} weighted by areas of individual land uses within each suborder. The grand total SOC storage in Ohio soils accounts for about 879 Tg of which 58% is in Alfisols because of extensive distribution, 16% in Mollisols, 10% in Inceptisols, 8% in Entisols, 5% in Ultisols, and only 3% is stored in Histosols due to a small area (Table 1).

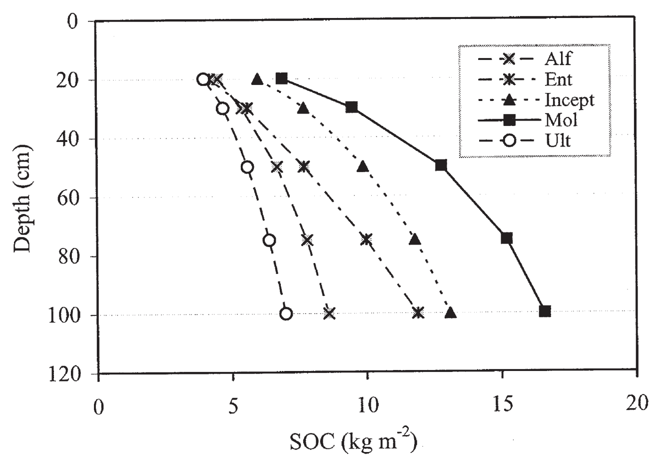

Fig. 3. Distribution of the cumulative arithmetic mean of soil organic C (SOC) pools for increasing soil depth.

Patterns of Soil Organic Carbon Pool Distribution in Relation to MLRAs

Estimates of SOC pools using the MLRA-taxonomic approach are presented in Table 2. The differences in SOC pools among land use categories depend not only on taxa but also on MLRAs. Averaging across all MLRAs for land uses within each order, the SOC pool in cropland is significantly higher than that in both forest and pasture lands for Entisols and Inceptisols, and significant differences are also present between forestland and pastureland for Alfisols and Inceptisols. Averaging across all MLRAs for each order and comparing them with the data presented in Table 1, the SOC pool size in Table 2 declines by 3.5 kg m^{-2} for Entisols, 1.1 kg m^{-2} for Inceptisols, and 0.2 kg m^{-2} for Mollisols, with an increase by 3.9 kg m^{-2} for Histosols and no change for other orders.

While averaging across land uses for each order and MLRA, the SOC pool in Histosols increases from 70 kg m^{-2} in MLRA 99 to 120 kg m^{-2} (derived from the data in Table 2) in MLRA 111, because Histosols in MLRA 99 are usually shallower (organic layers <85 cm in depth) than in MLRA 111 and 139. Excluding Histosols, Entisols exhibit the largest fluctuation with the highest mean in MLRA 111 and the lowest in MLRA 124, followed by Inceptisols which varied from 8.5 kg m^{-2} in MLRA 100 to 19.3 kg m^{-2} in MLRA 111. This variability in SOC pools among MLRAs can be attributed to the contrasting nature of orders in the various MLRAs. Entisols and Inceptisols in MLRA 111 occur primarily in floodplains and are derived from C-rich surface horizons eroded and deposited from surrounding uplands, whereas Entisols in MLRA 124 occur mainly on steep side-slopes and are shallow. Inceptisols in MLRA 100 are weakly developed with C poor surface horizons. The least variation is observed in Alfisols. Of all mineral soils, Mollisols contain the highest C pool in all MLRAs with an exception in MLRA 111 where Entisols and Inceptisols occurring primarily in floodplains have higher SOC pools. The least variation in the SOC pool is observed in MLRA 111, but the widest in MLRA 114 due to the greatest fluctuation in drainage class, particularly for forestland. As could be expected, the final area-weighted means for mineral soils associ-

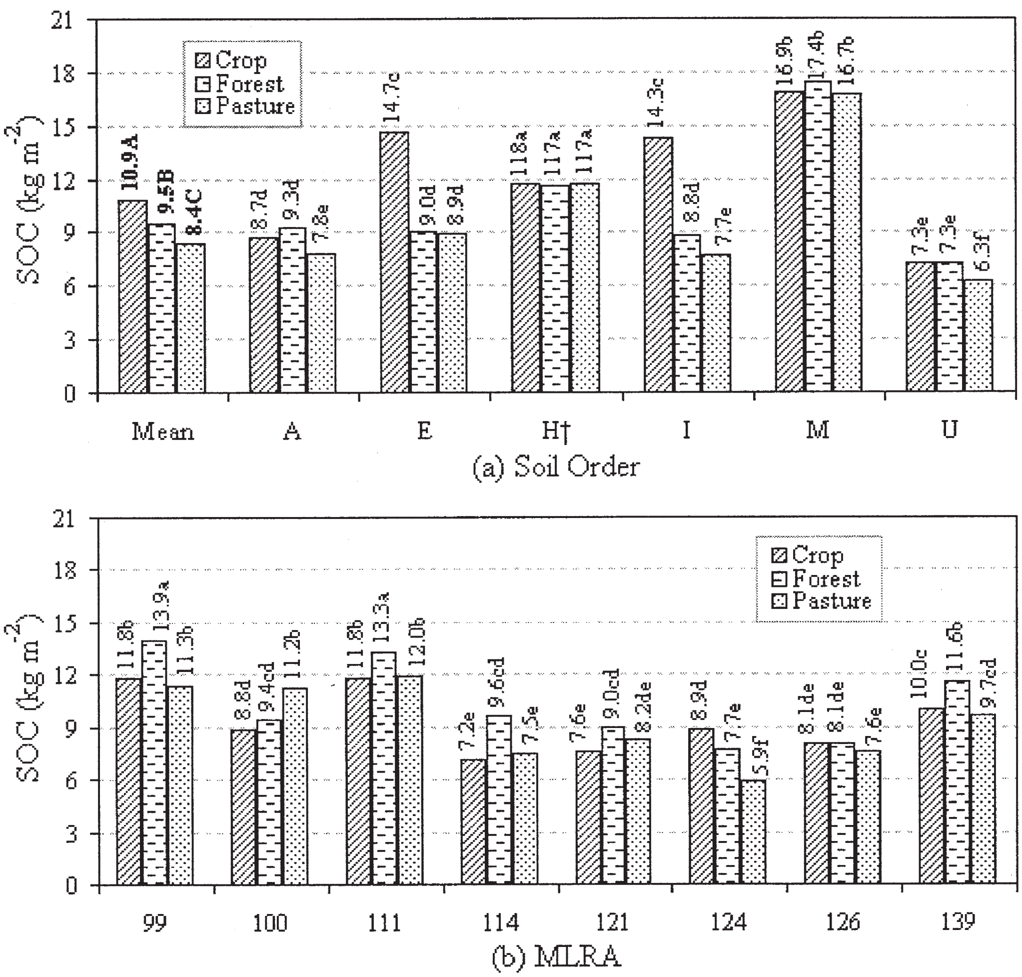

Fig. 4. Soil organic C pool (SOC) means for three land use categories associated with: (a) soil orders, estimated using taxonomic approach and weighted by the area of each land use within suborders (A, E, H, I, M, and U stand for Alfisols, Entisols, Histosols, Inceptisols, and Ultisols, respectively), and (b) Major Land Resource Areas (MLRAs), estimated using the MLRA-taxonomic approach and weighted by the area of each land use within soil orders. The same letters following numbers indicate no significant differences between them at α = 0.05. † Actual heights of these bars for Histosols are reduced by a factor of 10 for easy graphing.

ated with individual MLRAs, ranging from 7.7 to 12.0 kg m^{-2}, do not fluctuate as much as those for mineral soil orders which range from 7.1 kg m^{-2} in Ultisols to 16.9 kg m^{-2} in Mollisols (Table 2). The reduced variability in SOC pools among MLRAs relative to soil orders can be attributed to differences in the proportions of various soils rather than major differences in soil characteristics.

Averaging across all orders for each MLRA, the SOC pools with respect to MLRAs are also presented in Table 2 and their spatial distribution patterns are illustrated in Fig. 1. The highest SOC pools occur in MLRA 99, 111, and 139. These MLRAs comprise the Wisconsian Till plain (MLRA 111 and 139) and the Ancient Maumee Lake plain (MLRA 99) where there are high percentages of poorly drained soils. On the other hand, low SOC pools are present in the MLRA 114, 121, 124, and 126. These MLRAs, locating in the south and southeastern regions of the state, are occupied by mineral soils that mainly occur on more sloping terrain and are better drained or Illinoisan-aged, highly weathered till soils (MLRA 114).

Statewide, the mean of SOC pool estimated using the MLRA-taxonomic approach is 10.2 ± 2.8 kg m^{-2} and the grand total SOC storage in Ohio is about 853 Tg with a coefficient of variation (CV) of 28%. Both numbers are respectively little bit smaller than those obtained from the taxonomic approach. In comparison with the taxonomic approach, the MLRA-taxonomic approach can count and specify spatial variation in SOC pool at a more detail scale, therefore generate results with less error.

Land Use Effects on Soil Organic Carbon Pools

Land use effects on SOC sequestration are widely recognized (Detwiler, 1986; Mann, 1986; Schlesinger, 1986; Post and Mann, 1990; Davidson and Ackerman, 1993). However, the interpretation of such effects may be difficult due to the confounding influences of preferential selection of land for cropland use and site topographic characteristics.

The data in Fig. 4a show that the means of SOC pools of Alfisols and Mollisols tend to be higher in forestland than in cropland, but the differences are not significant. Cropland associated with both Entisols and Inceptisols have significantly larger SOC pools than pastureland and forestland do. These data suggest that the effect of land use depends on soil taxon and that no general relationship exists between land use and SOC pools. However, it is more probable that this apparent lack of a relationship is due to preferential selection of land for cropland use. For example, Entisols and Inceptisols that occur in floodplains are preferentially selected for cropland use whereas Entisols and Inceptisols occurring on steep slopes in southeastern Ohio with low SOC pools were never cultivated or have reverted to forest after a relatively unsuccessful conversion to cropland. This hypothesis is supported by reference to data for MLRA 124 (Fig. 4b). The dominant cropland in MLRA 124 is in the floodplains whereas forest and pasture are prevalent on steep valley wall slopes where soils have low SOC pools. In all the other MLRAs, except for MLRA 100, forestland contained a larger SOC pool than either cropland or pastureland. Confounding factors make it difficult to interpret the differences in SOC dynamics at an order level or MLRA scale.

Land use distribution is generally topography dependent. As indicated in Table 3, it is apparent that lower SOC pools corresponded to steeper slopes with respect to soil taxa, especially for forestland and pastureland where Inceptisols are located on steep slopes, followed

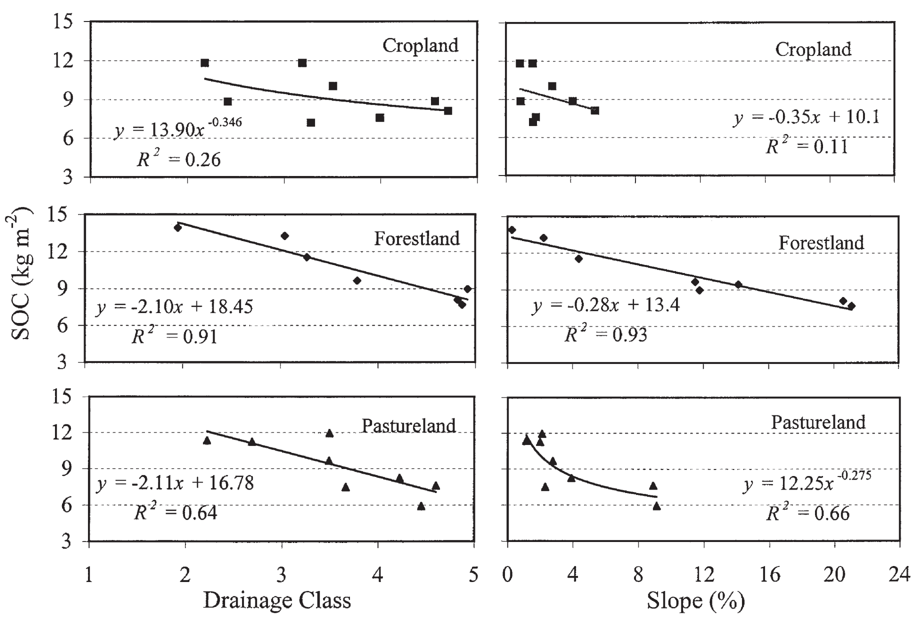

Fig. 5. Relationships between the soil organic C (SOC) pools in MLRAs and site variables. Mean values of the SOC pool, drainage class index, and slope percentage were calculated using the MLRA-taxonomic approach. The data of drainage class and slope are from the pedon records in the attribute data table and the areas for area-weighted means are derived from the attribute table associated with the taxon-land use-MLRA theme. Drainage class 0, 1, 2, …, 6 are assigned for very poorly, poorly, somewhat poorly, moderately well, well, somewhat excessively, and excessively drained, respectively.

by Ultisols, Entisols, and Alfisols. Mollisols and Histosols are distributed on level and gentle slopes. Nevertheless, MLRAs, as initially defined, are topography specific. The data in Table 4 show that MLRA 121, 124, and 126 are characterized by steep slopes and well-drained soils, in contrast to gently sloping and poorly drained soils which are common in MLRA 99, 111, and 139.

The impacts of slope and drainage classes on SOC pools are illustrated in Fig. 5. A very strongly negative linear relationship between SOC pool and slope gradient was observed in forestland ($R^2 = 0.93$, $p < 0.001$), and a strongly negative quadratic relationship in pastureland ($R^2 = 0.66$, $p < 0.01$). Significant impacts of drainage condition on SOC pool are well expressed by a linear regression relation for forestland ($R^2 = 0.91$, $p < 0.001$) and pastureland ($R^2 = 0.64$, $p < 0.01$). No pronounced relationship was observed in cropland because no significant differences in slope and drainage classes can be identified for the selected soil pedons. Therefore, the large SOC pool in cropland is attributed to landscape and soil characteristics of areas selected for cultivation which preferentially selects soils with high SOC pools and does not mean that arable land has a higher potential for SOC accumulation than forest and pasture. On the contrary, much higher SOC pool size can be observed in forests compared with other land uses when site conditions are comparable.

CONCLUSIONS

Land use influences on SOC pools are confounded by preferential selection of land for cropland use and differentiated by site slope and drainage classes. Soil organic C pools in forestland and pastureland depend strongly on both site slope and drainage classes, implying that the interpretation of differences in SOC pools among land use systems in association with soil taxon and MLRA must be tempered by an understanding of landscape and soil characteristics used in decisions regarding land uses. Results of this study should be particularly useful for SOC credit accounting and future SOC sequestration projections at an intrastate MLRA scale.

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